IMPROVED MEASUREMENT OF CP ASYMMETRY IN THE NEUTRAL B MESON SYSTEM

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We present an improved measurement of the standard model CP violation parameter $\sin 2\phi_1$ (also known as $\sin 2\beta$) based on a sample of 45×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. One neutral B meson is reconstructed in the $J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$, $J/\psi K^{*0}$, or $J/\psi K_L^0$ CP-eigenstate decay channel and the flavor of accompanying B meson is identified from its decay products. From the asymmetry in the distribution of the time intervals between the two B meson decay points, we obtain $\sin 2\phi_1 = 0.82 \pm 0.12(\mathrm{stat}) \pm 0.05(\mathrm{syst})$. The result is preliminary.

In the Standard Model (SM), CP violation arises from an irreducible complex phase in the weak interaction quark mixing matrix (CKM matrix)[1]. In particular, the SM predicts a CP violating asymmetry in the time-dependent rates for B^0 and $\overline{B}^0$ decays to a common CP eigenstate, f_{CP}, with negligible corrections from strong interactions[2]:

$$A(t) \equiv \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m_d t, \qquad (1)$$

where $\Gamma(B^0, \overline{B}^0 \to f_{CP})$ is the decay rate for a B^0 or $\overline{B}^0$ to f_{CP} dominated by $b \to c\overline{c}s$ transition at a proper time t after production, ξ_f is the CP eigenvalue of f_{CP}, Δm_d is the mass difference between the two B^0 mass eigenstates, and ϕ_1 is one of the three interior angles of the CKM unitarity triangle, defined as $\phi_1 \equiv \pi - \arg(-V_{tb}^* V_{td} / - V_{cb}^* V_{cd})$.

In this paper, we report an improved measurement of $\sin 2\phi_1$ using 45×10^6 $B\overline{B}$ pairs ($42\ \mathrm{fb}^{-1}$) collected with the Belle detector[3] at the $\Upsilon(4S)$ resonance in collisions of 8.0 GeV e^-

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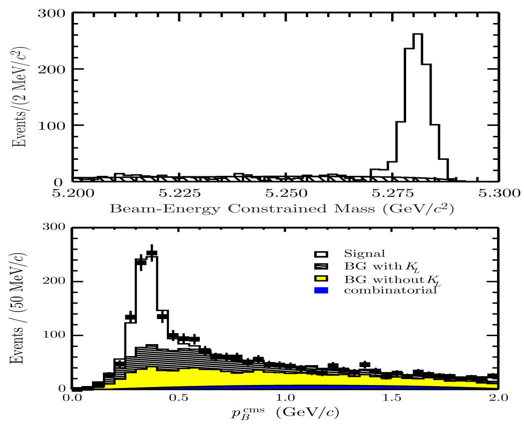

Figure 1: (Top) the beam-energy constrained mass distribution for all decay modes combined other than $J/\psi K_L^0$. (Bottom) the $p_B^{\rm cms}$ distribution for $B^0 \to J/\psi K_L^0$ candidates with the results of the fit.

Table 1: The numbers of observed candidates ($N_{\rm ev}$) and the estimated background ($N_{\rm bkg}$) in the signal region for each f_{CP} mode.

Mode	$N_{\rm ev}$	$N_{\rm bkg}$
$J/\psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$	636	31.2
$J/\psi(\ell^+\ell^-)K_S^0(\pi^0\pi^0)$	102	20.8
$\psi(2S)(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$	49	2.4
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0(\pi^+\pi^-)$	57	4.3
$\chi_{c1}(J/\psi\gamma)K_S^0(\pi^+\pi^-)$	34	2.3
$\eta_c(K^+K^-\pi^0)K_S^0(\pi^+\pi^-)$	39	11.1
$\eta_c(K_S^0K^-\pi^+)K_S^0(\pi^+\pi^-)$	33	8.9
$J/\psi(\ell^+\ell^-)K^{*0}(K_S^0\pi^0)$	55	6.0
$J/\psi(\ell^+\ell^-)K_L^0$	767	307

to 3.5 GeV e^+ at KEKB[4], where two B mesons reside in a coherent p-wave state until one of them decays. The decay of one of the B mesons to a self-tagging state, $f_{\rm tag}$, *i.e.*, a final state that distinguishes B^0 and $\overline{B}^0$, at a time $t_{\rm tag}$ projects the accompanying meson onto the opposite b-flavor at that time; this meson decays to f_{CP} at time t_{CP}. The CP violation manifests itself as an asymmetry $A(\Delta t)$, where Δt is the proper time interval $\Delta t \equiv t_{CP} - t_{\rm tag}$. At KEKB, the $\Upsilon(4S)$ resonance is produced with a boost of $\beta\gamma = 0.425$ along the electron beam direction (z direction). Because the B^0 and $\overline{B}^0$ mesons are nearly at rest in the $\Upsilon(4S)$ center of mass system (cms), Δt can be determined as $\Delta t \simeq \Delta z/(\beta\gamma)c$, where Δz is the z distance between the f_{CP} and $f_{\rm tag}$ decay vertices, $\Delta z \equiv z_{CP} - z_{\rm tag}$. The average value for Δz is approximately 200 μm.

We reconstruct B^0 decays to the following CP eigenstates[b]: $J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$ for $\xi_f = -1$ and $J/\psi K_L^0$ for $\xi_f = +1$. We also use $B^0 \to J/\psi K^{*0}$ decays where $K^{*0} \to K_S^0\pi^0$. Here the final state is a mixture of even and odd CP, depending on the relative orbital angular momentum of the J/ψ and K^{*0}. We find that the final state is primarily ξ_f; the $\xi_f = -1$ fraction is $0.19 \pm 0.04({\rm stat}) \pm 0.04({\rm syst})$[5]. For reconstructed B candidates except $J/\psi K_L^0$, we identify B decays using the energy difference $\Delta E \equiv E_B^{\rm cms} - E_{\rm beam}^{\rm cms}$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^{\rm cms})^2 - (p_B^{\rm cms})^2}$, where $E_{\rm beam}^{\rm cms}$, $E_B^{\rm cms}$, and $p_B^{\rm cms}$ are the beam energy, the energy, and the momentum of the reconstructed B candidate in the cms, respectively. Figure 1 (top) shows the $M_{\rm bc}$ distributions for all B^0 candidates except for $B^0 \to J/\psi K_L^0$ that are found in the ΔE signal region. Table 1 lists the numbers of observed candidates ($N_{\rm ev}$) and the background ($N_{\rm bkg}$) estimated by extrapolating the rate in the non-signal ΔE vs $M_{\rm bc}$ region into the signal region. Candidate $B^0 \to J/\psi K_L^0$ decays are selected by requiring electromagnetic calorimeter (ECL) and/or K_L^0 and muon detector (KLM) hit patterns that are consistent with the presence of a shower induced by a neutral hadron. The centroid of the shower is required to be in a 45° cone centered on the K_L^0 direction that is inferred from two-body decay kinematics and the measured four-momentum of the J/ψ. Figure 1 (bottom) shows the $p_B^{\rm cms}$ distribution, calculated with the $B^0 \to J/\psi K_L^0$ two-body decay hypothesis. The histograms are the results of a fit to the signal and background distributions. There are 767 entries in total in the region $0.20 \le p_B^{\rm cms} \le 0.40$ GeV/c with KLM clusters and in $0.20 \le p_B^{\rm cms} \le 0.40$ GeV/c with clusters in the ECL only. The fit finds a signal purity of 60%. The reconstruction and selection criteria for used channels are described elsewhere[6].

Leptons, charged pions, kaons, and Λ baryons that are not associated with a reconstructed CP eigenstate decay are used to identify the b-flavor of the accompanying B meson; high mo-

[b] Throughout this paper, when a decay mode is quoted, the inclusion of the charge conjugation mode is implied.

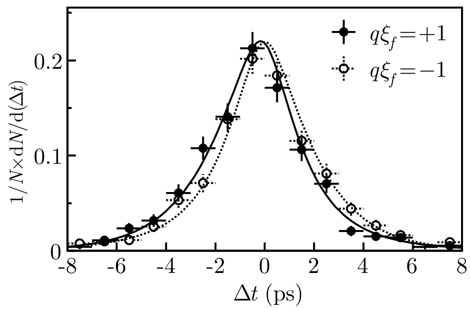

Figure 2: Δt distributions for the events with $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points). The results of the global fit with $\sin 2\phi_1 = 0.82$ are shown as solid and dashed curves, respectively.

Table 2: The values of $\sin 2\phi_1$ for various subsamples (statistical errors only).

Sample	$\sin 2\phi_1$
$f_{\rm tag} = B^0$ $(q = +1)$	0.60 ± 0.19
$f_{\rm tag} = \overline{B}^0$ $(q = -1)$	0.99 ± 0.16
$J/\psi K_S^0(\pi^+\pi^-)$	0.67 ± 0.18
$(c\overline{c})K_S^0$ except $J/\psi K_S^0(\pi^+\pi^-)$	0.88 ± 0.31
$J/\psi K_L^0$	1.14 ± 0.23
$J/\psi K^{*0}(K_S^0\pi^0)$	1.62 ± 1.10
All	0.82 ± 0.12

mentum leptons from $b \to c\ell^-\overline{\nu}$, lower momentum leptons from $c \to s\ell^-\overline{\nu}$, charged kaons and Λ baryons from $b \to c \to s$, fast pions from $B^0 \to D^{(*)-}(\pi^+, \rho^+, a_1^+$, etc.), and slow pions from $D^{*-} \to \overline{D}^0\pi^-$. Using those tracks, two parameters, q and r, are assigned to an event. The first, q, has the discrete values $q = \pm 1$ that is $+1(-1)$ when $B_{\rm tag}$ is likely to be a $B^0(\overline{B}^0)$, and the parameter r is an event-by-event flavor-tagging dilution factor ranging from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six intervals of r, according to flavor purity; the wrong-tag probabilities, w_l $(l = 1, 6)$, for the final fit are determined directly from data. The decay to exclusively reconstructed self-tagged channels are utilized to obtain w_l using time-dependent B^0-$\overline{B}^0$ mixing oscillation: $(N_{\rm OF} - N_{\rm SF})/(N_{\rm OF} + N_{\rm SF}) = (1 - 2w_l)\cos(\Delta m_d \Delta t)$. Here $N_{\rm OF}$ and $N_{\rm SF}$ are the numbers of opposite and same flavor events. The total effective tagging efficiency is $\sum_{l=1}^{6} f_l(1 - 2w_l)^2 = 0.270 \pm 0.008({\rm stat})^{+0.006}_{-0.009}({\rm syst})$, where f_l is the event fraction for each r interval.

The vertex position for f_{CP} is reconstructed using leptons from J/ψ decay and that for $f_{\rm tag}$ is obtained with well reconstructed tracks not assigned to f_{CP}. Tracks that form a K_S^0 invariant mass are not used. Each vertex position is required to be consistent with the interaction point profile smeared in the r-ϕ plane by the B meson decay length. The requirement enables us to determine a vertex even with a single track. The fraction of such vertices is about 10% for z_{CP} and 30% for $z_{\rm tag}$. A proper-time interval resolution, $R_{\rm sig}(\Delta t)$, consists of a convolution of four components: detector resolution for z_{CP} and $z_{\rm tag}$, shift in the $z_{\rm tag}$ reconstruction due to secondary tracks originated from charmed hadrons such as D^+ and D^0, and smearing effect due to kinematic approximation in converting Δz to Δt. We find broad outlier components in Δz distributions due to mis-reconstruction, which are represented by Gaussian distributions. We simultaneously determine ten resolution parameters from data with a fit of neutral and charged B meson lifetimes[7] and obtain a Δt resolution of ~ 1.56 ps (rms). The width and the fraction of the outlier component are determined to be 36^{+5}_{-4} ps, and $(0.06^{+0.03}_{-0.02})$% or (3.1 ± 0.4)% (multiple- or single-track case).

After vertexing we find 766 events with $q = +1$ flavor tags and 784 events with $q = -1$. Figure 2 shows the observed Δt distributions for the $q\xi_f = +1$ (solid points) and $q\xi_f = -1$ (open points) event samples. The asymmetry between two distributions demonstrates the violation of the CP symmetry. We determine $\sin 2\phi_1$ from an unbinned maximum-likelihood fit to the observed Δt distributions. The probability density function (pdf) expected for the signal distribution is given by

$$\mathcal{P}_{\rm sig}(\Delta t, q, w_l, \xi_f) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}[1 - q\xi_f(1 - 2w_l)\sin 2\phi_1 \sin \Delta m_d \Delta t], \qquad (2)$$

where we fix the B^0 lifetime and mass difference at their world average values[8]. Each pdf is

convolved with the appropriate $R(\Delta t)$ to determine the likelihood value for each event as a function of $\sin 2\phi_1$:

$$
\begin{aligned}
P_i &= (1-f_{\rm ol})\int\Big[f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t', q, w_l, \xi_f)R_{\rm sig}(\Delta t-\Delta t') \\
&\quad + (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(\Delta t')R_{\rm bkg}(\Delta t-\Delta t')\Big]d\Delta t' + f_{\rm ol}P_{\rm ol}(\Delta t), \qquad (3)
\end{aligned}
$$

where $f_{\rm sig}$ is the signal probability calculated as a function of $p_B^{\rm cms}$ for $J/\psi K_L^0$ and of ΔE and $M_{\rm bc}$ for other modes. $\mathcal{P}_{\rm bkg}(\Delta t)$ is a pdf for combinatorial background events that is modeled as a sum of exponential and prompt components. It is convolved with a sum of two Gaussians, $R_{\rm bkg}$. $P_{\rm ol}$ and $f_{\rm ol}$ are the pdf and the fraction for the outlier component. The only free parameter in the final fit is $\sin 2\phi_1$, which is determined by maximizing the likelihood function $L = \prod_i P_i$, where the product is over all events. The preliminary result of the fit is

$$\sin 2\phi_1 = 0.82 \pm 0.12({\rm stat}) \pm 0.05({\rm syst}).$$

The systematic error is dominated by uncertainties due to effects of the tails of the vertex distribution (± 0.030). Other significant contributions come from uncertainties (a) in w_l ($^{+0.024}_{-0.026}$); (b) in the resolution function parameters ($^{+0.022}_{-0.019}$); (c) in the $J/\psi K_L^0$ background fraction ($^{+0.014}_{-0.015}$). The errors introduced by uncertainties in Δm_d and τ_{B^0} are 0.01 or less.

A number of checks on the measurement are performed. Table 2 lists the results obtained by applying the same analysis to various subsamples. All values are statistically consistent with each other. The result is unchanged if we use the w_l's determined separately for $f_{\rm tag} = B^0$ and $\overline{B}^0$. A fit to the non-CP eigenstate self-tagged modes $B^0 \to D^{(*)-}\pi^+$, $D^{*-}\rho^+$, and $J/\psi K^{*0}(K^+\pi^-)$, where no asymmetry is expected, yields 0.05 ± 0.04.

We also measure CP violating asymmetry in $B^0 \to \eta' K_S^0$ decays based on 45×10^6 $B\overline{B}$ pairs. Numbers of fully reconstructed events for $\eta(\gamma\gamma)\pi\pi K_S^0$ and for $\rho\gamma K_S^0$ are $27.7^{+6.2}_{-5.5}$ and $45.4^{+8.6}_{-7.9}$, respectively. Flavor of the accompanying B meson is identified from its decay products. The decay rate has a time dependence given by

$$\mathcal{P}_{\rm sig}(\Delta t, q, w_l) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q(1-2w_l)[S\sin(\Delta m_d \Delta t) + C\cos(\Delta m_d\Delta t)]\Big\}. \qquad (4)$$

From the asymmetry in the Δt distribution, we obtain $S = 0.27^{+0.54}_{-0.55}({\rm stat}) \pm 0.07({\rm syst})$ and $C = 0.12 \pm 0.32({\rm stat}) \pm 0.07({\rm syst})$.

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